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# THESIS

**NORTH PACIFIC TROPICAL CYCLONES AND TELECONNECTIONS**

by

David C. Budzko

March 2005

Thesis Advisor: C.-P. Chang

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# NORTH PACIFIC TROPICAL CYCLONES AND TELECONNECTIONS

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Submitted in partial fulfillment of the
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# ABSTRACT

This thesis investigated the hypothesis that variations in tropical cyclone (TC) activity in the western North Pacific (WNP) may affect the teleconnection between the tropical WNP and North America. The teleconnection patterns of the 500 hPa geopotential height between a base point in the WNP (20°N 115°E) and a domain over North America (30°-45°N, 70°-90°W) from 1951-2001 were examined. The 25 most active and the 25 least active TC years for two regions with the highest climatological average of TC activity, near the Philippines and Taiwan, respectively, were compared to determine if stronger teleconnection patterns occur during the more active years. For both regions, the correlation pattern is significant during active years and insignificant during inactive years, with the results based on TC activity in the Philippines region showing a larger difference. An analysis of 500 hPa mean winds showed weaker winds in the midlatitudes during active TC years when the teleconnection is stronger, which suggests that the teleconnection may consist mainly of Lau and Weng's (2000) zonally-elongated mode (Mode 1). Further cross correlations of the geopotential height and TC frequency parameters with the tropical eastern and western Pacific sea-surface temperatures (SST's) showed a significant correlation between TC activity and tropical eastern Pacific SST's, but the North America–WNP correlation is unlikely to be a result of a direct influence of SST's on the two regions.

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# I. INTRODUCTION

## A. IMPORTANCE OF RESEARCH TO THE DEPARTMENT OF DEFENSE

With nearly 300,000 military personnel forward deployed and based across the Pacific Rim to support military operations and peacetime engagements, understanding the climatology of this vast region is an important component of weather forecasting and its role in operational planning. In turn, force protection and, ultimately, mission success stems from a successful integration of climatological data into the mission planning process. Numerous examples throughout the history of warfare have shown that missions can either benefit from or be adversely impacted by the effects of weather. Conducting research into the climatology of the Pacific region is critical to advancing our understanding of the scales of atmospheric phenomena that can potentially impact operations in and adjacent to this nearly 100 million square mile area. This thesis will illustrate, however, that atmospheric disturbances in the Pacific can also impact locations quite distant from the source via teleconnections. For these reasons, continuing efforts to research Pacific climatology are needed to ensure Air Force meteorology continues to provide Department of Defense (DoD) strategic planners and warfighters both short and long-term climate variability forecasts and other critical weather data while enhancing our understanding of atmospheric teleconnections and their regional and global impacts.

According to the United States Pacific Command (PACOM), the total U.S. force in this organization's Area of Responsibility (AOR) is comprised of the service components, subordinate unified commands, and joint task forces, consisting of not only military, but civilian personnel as well (2004). The Air Force, under the command of Pacific Air Forces, has approximately 45,000 military and civilian personnel. In addition, there are about 400 aircraft to support offensive and defensive air operations as well as in-theater air refueling missions (PACOM 2004). The U.S. Army, Navy, and Marine Corps also position substantial forces throughout the Pacific and conduct a wide range of missions to achieve national security objectives.

In addition to the 300,000 military personnel stationed in the Pacific, PACOM reports that in their AOR, which totals 50 percent of the Earth's surface, the world's six largest armed forces are located here (PACOM 2004). The U.S. military participates in five of the seven worldwide U.S. mutual defense treaties in this region as well. From a demographic and economic perspective, 60 percent of the world's population lives in this AOR, comprising 43 countries, 20 territories and possessions, and 10 U.S. territories. "35 percent of U.S. trade is within the region, amounting to more than $548 billion in 1998" (PACOM 2004). Thus, the Pacific realm is a hub for not only a strong military presence, but also for population centers, commerce, and other economic and political interests. Because one of the chief mandates of the DoD is to ensure the safeguarding of U.S. political and economic interests in this region and around the world, continued research into Pacific climatology and teleconnections benefits the DoD whose missions can either exploit, or succumb to, the effects of weather.

## B. PREVIOUS NORTHWEST PACIFIC TROPICAL CYCLONE STUDIES

Many important studies of tropical cyclone (TC) activity in the western North Pacific (WNP) have been conducted to investigate variations in frequency, intensity and storm track. TC's in the WNP are more frequent and more intense than storms in other ocean basins (Ho et al. 2004). Often-favorable thermodynamic and dynamic atmospheric conditions in this region promote frequent TC formation and development. While most TC's generally develop over tropical oceans where the SST's are higher than 26°C, this is not the case in the South Atlantic and Southeast Pacific Oceans where other environmental factors prevent TC formation. Vertical wind shear, mid-tropospheric moisture amounts and momentum flux convergence are among a few of the environmental factors that influence whether or not TC's will form and develop. Previous work in TC's have focused on these factors as well as broader interannual and interdecadal climate changes that have either promoted, or curtailed, TC activity in the WNP.

### 1. Interannual Variations

One such study that focused on interannual and interdecadal variations in WNP TC activity was Chan (2004), which examined potential physical mechanisms that may explain these variations. Chan (2004) pointed out in his investigation, however, that an understanding of interdecadal variations must first come from investigating interannual variations. To that end, Chan (2004) identified two atmospheric and oceanographic oscillations as significantly contributing to these interannual variations. The first of these oscillations is the El Nino/Southern Oscillation (ENSO). Previously, Chan (1985) found a significant relationship between the annual numbers of typhoons over the WNP to the Southern Oscillation Index (SOI) on a period of 3 to 3.5 years. Many other studies, including Lander (1994), Chen et al. (1998), and Wang and Chan (2002), related interannual variations of TC activity to the planetary circulation changes associated with ENSO.

Wang and Chan (2002) and Chan (2004) found that prior to the onset of El Nino (EN), anomalously strong western equatorial winds over the Pacific enhance cyclonic shear farther east than the climatological average. This enhanced cyclonic shear also builds the monsoon trough farther east and to lower latitudes. As a result, TC's form farther southeast and can therefore last longer on their generally westward propagation. After EN subsides, the La Nina (LN) event follows with anomalous easterly equatorial winds, which reduce the cyclonic shear and create an unfavorable environment for TC's to develop. Wang et al. (2000) also found an anomalous anticyclone that tended to form east of the Philippines during the year following EN, which hindered TC formation and development and accounted for a below-normal number of TC's. Thus, TC activity is affected by occurrences of ENSO events. But Zhang et al. (1990) illustrated that the SOI associated with ENSO only explained about 40% of the TC activity variance in the WNP. Chan (2004) suggested that the remaining variance may be significantly explained by the stratospheric Quasi-biennial Oscillation (QBO).

Investigators of Atlantic basin TC frequency know that Gray (1984) has linked TC frequency in this region to the QBO. Gray et al. (1992) found that intense hurricane occurrence was almost three times more likely during the westerly phase of the QBO as that of the easterly phase (Chan 2004). Zhang et al. (1994) examined TC frequency in the WNP from 1884-1988 to see what role QBO had in the Pacific basin in affecting TC activity. Zhang et al. (1994) found that TC activity was enhanced during westerly phases of the QBO. Chan (1995) further found a significant correlation in the time series between WNP TC activity and the zonal winds at 30 and 50 hPa that corresponded with the QBO frequency. This correlation weakened, however, during ENSO years, which seemed to indicate that the ENSO is stronger. Chan (1995) also discussed the possibility of other factors influencing TC activity in the WNP as well.

**2. Interdecadal Variations**

Although numerous questions remain about the exact nature of the relationship among ENSO, QBO, and other environmental factors affecting TC frequency variance in the WNP, Chan (2004) and other studies of interannual variations provide potential explanations for interdecadal variances. Earlier investigations of interdecadal variances included Zhang et al. (1994) who, while studying the QBO and interannual variances, also uncovered interdecadal oscillations in TC frequency. However, the physical explanation for these oscillations was not addressed in this study. Yumoto and Matsuura (2001) grouped annual numbers of TC's into high-frequency (HP) and low-frequency (LP) periods. They found the main difference between the HP and LP periods was between the months of July to October. Their study also illustrated that in the areas where TC's are most likely to form in the WNP (i.e., east of the Philippines), the local SST's play no apparent role in increasing or decreasing TC activity. Chan and Liu (2004) verified this result when they removed central and eastern equatorial SST's from the correlation study, which demonstrated the potential impact of ENSO (Yumoto and Matsuura 2001).

More recently, Ho et al. (2004) attributed interdecadal changes in WNP TC frequency to the enlargement, strengthening, and southwestward extension

of the WNP subtropical ridge. This modification of the subtropical ridge was linked to significant interdecadal changes in the number of TC's in the Philippine Sea and East China Sea. Matsurra et al. (2003) found a similar result when studying interdecadal TC variations due to forcing of the WNP atmospheric circulation by central and eastern Pacific SST's. The SST anomalies that this study found corresponded to the same area as that of the North Pacific subtropical high. More research is needed to address the significance of the correlation between changes in the subtropical ridge, as well as other factors such as the Pacific Decadal Oscillation, and WNP TC climatology and SST's.

Other aspects of WNP TC climatology also require additional research to uncover how TC frequencies, tracks and intensities both effect atmospheric changes locally and remotely, for example through geopotential height anomalies, and how TC's respond to large-scale climate changes (i.e., ENSO, WNP SST anomalies, etc.). One way these effects can be felt distant from its source is through teleconnections. Studies of teleconnections have also been an on-going endeavor for decades as researchers attempt to link anomalies in one part of the world with energy sources in another. Previous teleconnection research is presented in Section C.

## C. PREVIOUS RESEARCH IN TELECONNECTIONS

For more than 50 years, atmospheric teleconnections have been studied in an attempt to, in part, identify and document significant global wave patterns and correlations to assess their impacts vis-à-vis the tropics and extratropics. For the majority of this period, research in teleconnections has been focused on the Northern Hemisphere (NH) winter when the jet stream is strongest. Relatively little research on teleconnection patterns has been conducted during the NH summer when the mean flow has very different large-scale circulation patterns. These patterns are characterized by a relatively weak, and northward-displaced, westerly jet stream (Lau and Peng 1992).

### 1. Wallace and Gutzler's (1981) Study

Wallace and Gutzler's (1981) work is perhaps one of the most important earlier studies on teleconnections. Despite emphasizing winter teleconnections, this paper provides valuable data to compare summer and winter teleconnections patterns by their use of an objective method to identify and describe the strongest teleconnection patterns. These patterns include (1) the Eastern Atlantic pattern; (2) the Pacific/North American pattern; (3) the Western Atlantic pattern; (4) the Western Pacific pattern; and (5) the Eurasian pattern. Data from their objective method were applied to an independent data set so that the reproducibility of the patterns could be tested (Wallace and Gutzler 1981). Their work also provides a means to measure the reliability of the results obtained through one-point correlation coefficients.

The definition of teleconnections was given by Wallace and Gutzler (1981) as: "Significant simultaneous correlations between temporal fluctuations in meteorological parameters at widely separated points on earth." While this definition of teleconnections can be generally agreed upon, a review of literature on this subject suggests that horizontal structural relationships among teleconnections may not be so widely accepted. Wallace and Gutzler (1981) pointed out, "Much of the literature...is difficult to interrelate and synthesize because of the lack of unique or universally agreed on criteria and procedures for defining horizontal structural relationships." Nonetheless, most investigators of teleconnections rely upon one or more well-known parameters: sea-level pressure, geopotential height, and/or air or sea-surface temperatures. In using these parameters, investigators will likely apply some linear combination of one or more of these parameters at some number of locations. Another approach is to use this technique in conjunction with some variation of a time series (Wallace and Gutzler 1981). Wallace and Gutzler (1981) used data from a 15-year period including mean sea-level pressures and 500 hPa geopotential heights to calculate temporal correlation coefficients among grid points.

Through a review of publications, Wallace and Gutzler (1981) identified four major standing oscillations or patterns in the NH winter: (1) the North Atlantic

Oscillation; (2) the North Pacific Oscillation; (3) the Pacific/North American pattern; and (4) what Lorenz (1951) described as a "zonally symmetric see-saw between sea-level pressures at the poles to temperature latitudes." By using these major patterns as a starting point, Wallace and Gutzler (1981) used a 15-year period of 500 hPa geopotential height data to calculate one-point correlation coefficients, which then allowed the authors to identify the most prominent patterns. These prominent patterns include the five outlined earlier: (1) the Eastern Atlantic pattern; (2) the Pacific/North American pattern; (3) the Western Atlantic pattern; (4) the Western Pacific pattern; and (5) the Eurasian pattern. The authors also use an eigenvector analysis to address the possibility that "the patterns...are unique, or at least that they are not linear combinations of a smaller number of more fundamental patterns." Through this eigenvector analysis, Wallace and Gutzler (1981) found that "there is strong correspondence between the shapes of the eigenvector patterns and the teleconnection patterns", but there were some differences also. "On the whole, the teleconnection patterns tend to be somewhat more localized, with fewer strong centers of action..." However, both analysis methods bring certain advantages to displaying the structure of the correlation matrix.

The authors then attempted to identify the same teleconnection patterns by taking the results derived from their correlation coefficient matrix and applying them to an independent data set, which consisted of climatological data for December, January, and February extending from 1949-50 to 1961-62. Another difference from the correlation coefficient analysis was that after determining that the teleconnection patterns were similar at both the 500 and 700 hPa levels, the authors used 700 hPa data rather than 500 hPa data for their analysis. From this independent data set, the "700 hPa one-point correlation maps for a selection of grid points...in the five teleconnection patterns...appear to be qualitatively reproducible...but most of them show some diminution in sharpness." In contrast, "the eigenvector patterns are considerably less reproducible in the independent data set than are the one-point correlation maps." The authors concluded that these differences may be due to, among other factors, sampling

fluctuations or "systematic local biases in the 700 hPa height analyses during parts of the earlier data sample." Yet despite the variation in methods and differences in the reproducibility in the outcomes, Wallace and Gutzler (1981) provided substantive evidence as to the value of one-point correlation data, which are so widely used today to study teleconnections.

### 2. Nitta's (1987) Study

Another perspective on NH teleconnections is offered in Nitta (1987) who examined interannual and intraseasonal variations of convective activities in the tropical western Pacific during summer and their impact on the Northern Hemisphere circulation. Nitta (1987) used monthly mean amounts of high clouds in the western Pacific as well as SST and geopotential height data from a 6-year period from 1978 to 1983 to document impacts to NH summer circulations from both interannual and intraseasonal variations of convective activities in the tropical western Pacific. Nitta (1987) used the high-cloud amounts because these data are good indicators of convective activity and precipitation rate over the tropical oceans (Nitta 1986; Maruyama et al. 1986). Nitta (1987) used one-point correlation coefficients to illustrate teleconnection patterns in the form of 500 hPa geopotential height anomalies and wave trains from the tropical western Pacific to the North American west coast. Nitta's research proceeded from the premise that heat sources in the tropics play an important role in interannual and intraseasonal variations of global-scale atmospheric circulations.

In examining SST's, cloud amounts, and geopotential height data, Nitta (1987) outlined an apparent correlation between higher SST's in the tropical western Pacific, specifically near the Philippines, and a Rossby wave response across the North Pacific as well as high pressure anomalies over eastern Asia. This correlation by Nitta appears sound given the results that emerge from the author's two-point hypothesis: (1) "there exist wave trains of geopotential height emanating from the heat source region near Philippines to North America" and that "these wave trains appear to be generated when convective activities in the Philippine Sea become intense…" and (2) "During summers when the SST in the tropical western Pacific is about 1.0°C higher than normal, active convection

regions...are shifted northeastward" (1987). From this hypothesis and through observations, Nitta (1987) noted that Rossby waves essentially respond to this heating and thus propagate downstream across the North Pacific to North America, while anticyclonic circulation anomalies occur over East Asia and Japan. Nitta pointed to Kurihara and Tsuyuki's (1987) work to further substantiate the existence of this Rossby wave propagation emanating from the tropical western Pacific. Kurihara and Tsuyuki (1987) used a linear shallow-equation model in an analysis to show the atmospheric response to tropical forcing of the 1984 summer in the vicinity north of the Philippines. Their results quite accurately reflected Nitta's hypothesis in that (1) a ridge is located near Japan and (2) a wave-train extends across the North Pacific to the North American west coast. In addition, Kurihara and Tsuyuki (1987) used a one-point correlation map to illustrate 500 hPa heights with respect to cloud amounts, which is another technique employed by Nitta. Both sets of results outlined in these two papers seemed to agree on one conclusion: that Rossby waves are generated by the heat source anomaly near the Philippines and propagate through North America (Nitta 1987). However, these atmospheric responses seem to be present, regardless of whether the summer has SST's that are higher-than-normal (i.e., 1.0°C) or "cold" with the biggest difference among different summer seasons being the frequency with which the Rossby wave response and anticyclonic circulation anomalies take place (more frequently during warm SST summers) (Nitta 1987).

### 3. Lau and Peng's (1992) Study

Lau and Peng (1992), who also documented impacts from anomalous tropical forcing (i.e., the northward displacement of the Intertropical Convergence Zone (ITCZ) in the eastern Pacific), used a barotropic model in a series of intraseasonal numerical experiments to quantify the atmospheric response to an idealized local divergence source that stems from this northward displacement of the ITCZ. In addition, Lau and Peng (1992) examined, through another set of experiments, the tropical forcing mechanism in the western Pacific near the Philippines that Nitta (1987) also addressed in his paper. Lau and Peng (1992)

examined northern summertime teleconnection patterns that are responses to these anomalous tropical forcing mechanisms. Although different in their thesis and methodology, these authors maintained a similar goal of providing more detailed evidence of the important role teleconnections play in understanding global-scale atmospheric circulations and wave patterns.

Lau and Peng (1992) also examined the hypothesis that the 1988 drought over North America may be related to anomalous tropical latent heating resulting from a northward displacement of the ITCZ associated with the formation of cold water in the tropical Pacific. With this northerly displacement of the ITCZ, anomalous heating leads to a number of atmospheric responses, including: (1) an upper-level wave train that extends from the tropical eastern Pacific to North America and (2) the development of a high over the U.S. that shifts the normal summertime location of the jet stream northward. They pointed to the work by Trenberth et al. (1988), who also described this wave train pattern through the use of a linear baroclinic model using June climatological data.

Perhaps one of the more salient outcomes of Lau and Peng (1992) was that as the research examined tropical forcing between May and August, the atmospheric responses were found to be similar in June, July, and August, but different in May. Between June and August, they found that the common structure of the responses consists of an elongated upper-level high between the equator and 30°N near the forcing center, and an enhanced low near the Gulf of Alaska extending southeast toward the Gulf of Mexico, and a high over the midsection of the continental United States. In contrast, the May response is generally weaker everywhere and the response bears little resemblance to, and therefore appears to be decoupled from, the structure of the climatological flow. Lau and Peng (1992) suggested that this means a different mechanism of response in May. Lau and Peng (1992) postulated that the May mechanism was that of a "turning latitude" for the zonal mean wind component u as a function of wave number, which the authors compared for May and June. By interpreting solutions to the barotropic equation, the authors concluded that "There are two turning latitudes for the June mean flow and one for the May mean flow...these

turning latitudes play a key role in the scale selection for the extratropical response to tropical forcing because it determines the region in wave number domain in which propagating or decay solutions...can exist for a given latitude." Lau and Peng (1992) further added that, in addition to the number of turning latitudes for each month, there was also the absence of a southern zero-refractive index (turning latitude) for May due to the presence of westerly winds down to the equatorial region. Therefore, medium-to small-scale disturbances generated in the equatorial region are favored to propagate within and confined to the subtropics. Stated another way, the tropical forcing needs to exist at a particular latitude for the atmospheric responses to be felt downstream in the extratropics. This is an important consideration when attempting to understand and/or forecast summer teleconnections and impacts over a given season or year.

#### 4. Lau and Weng's (2000) Study

A more recent teleconnection study by Lau and Weng (2000) further discussed tropical forcing as a possible factor for summertime climate variability over North America. Using 44 years of data, including U.S. rainfall amounts, SST and wind and geopotential reanalysis data from 1944-1998, they found two major patterns, or modes, of summertime teleconnections. The first mode is a more zonally-elongated pattern that links the East Asian monsoon with North American rainfall. Mode 1 is associated with the 1993 flooding over the Midwestern U.S. and the U.S. east coast drought of 1998. The second mode is defined by Lau and Weng (2000) as a "wavetrain emanating from a region northeast of the Philippines, across the North Pacific rim, ending in a cyclone-anticyclone pair over North America." Mode 2 is also associated rainfall amounts over North America, but in the central U.S. as in the case of the 1988 drought.

#### 5. Summary of Teleconnection Studies

In their respective papers' concluding discussions, emphasis was given by the authors to what extent synoptic and global features or mechanisms exist to explain both the winter and summer teleconnections in their research. Wallace and Gutzler (1981) focused on observed patterns in winter and concede that "a

number of observational questions concerning the nature, causes, and dynamical implications of these…have not addressed…but are currently under active consideration." Nitta (1987), Lau and Peng (1992) and Lau and Weng (2000) stressed forcing mechanisms in the tropics such as convection and SST's to describe atmospheric responses and, in turn, summer teleconnections. Indeed, Lau and Peng (1992) suggested two possible mechanisms: (1) Rossby wave dispersion response from forcing north of 10°N in the eastern Pacific; and (2) "the excitation of a normal mode in a wavy basic state…stretching from the subtropical western Pacific across the Aleutians to North America." While Lau and Peng (1992), as well as numerous other investigators of teleconnections, suggested various mechanisms to explain these global atmospheric patterns, the authors of these publications articulated what all researchers of teleconnections undoubtedly acknowledge: there still exist many unresolved questions and uncertainties ranging from choice of model and its resolution to the scope of the study and the contribution of numerous variables, each of which potentially impacts the accuracy of the results.

## D. ORGANIZATION AND OBJECTIVE

As stated in the previous sections, many unresolved questions remain in the areas of WNP TC climatology and summer teleconnections. The role of SST's in the WNP, ENSO and the strength and location of the summer jet are among a few of the factors that must be considered when examining NH climate changes and anomalies. Another consideration in the NH summer is the influence of the Asian monsoon and its potential anomalous subtropical and extratropical forcing. Do more active Asian monsoon seasons significantly alter summer teleconnections compared to less active years? Because variations in, for example, precipitation can occur in one region of the world due to anomalous forcing mechanisms in another via teleconnections, would a more or less active TC period in the western Pacific impact weather conditions over North America? These are questions that are only now beginning to be addressed.

This thesis will address the role of WNP TC frequencies, tracks, and intensities and their possible impact on the NH summer climate, with particular emphasis on North America. The research will also examine how WNP TC climatology itself may be modified by the presence of other Pacific climate variabilities and anomalies. Fifty-one years of climatological data are examined, including NH 500 hPa geopotential heights, SST's, and WNP TC data to assess potential teleconnection patterns and correlations among these parameters. In turn, anomalous weather patterns and events over the Pacific Ocean and North America can then be potentially linked to WNP TC climatology. Because TC's release huge amounts of latent heat and represent forcing over the tropical western Pacific, we want to examine whether their activity affects teleconnection patterns.

However, to more fully understand potential teleconnection patterns between the western Pacific (WP) and North America (NA), other environmental influences besides TC activity must also be considered. Indeed, TC activity itself may also be affected by other environmental considerations which, in turn, influence a WP-NA connection. Chan (2004), for example, studied the possible relationship among the ENSO, WPSST and TC activity. Therefore, we need to study the relationships among these environmental conditions to TC activity and the 500 hPa height variability over NA in order to clarify whether the WP-NA teleconnections are affected by TC activity or whether both the TC activity and the teleconnection patterns are related to some of these other environmental conditions. There are also significant interdecadal variations of the climate over the Pacific, particularly a shift in the SST regime in the late 1970s that has changed the area and strength of the western North Pacific subtropical high (Chang et al 2000). Thus, the possible relationships among TC activity, NA 500 hPa height variability, and other variables examined in this study may be due to this decadal-scale climate shift rather than interannual variations. We will therefore need to separate the interannual variations from the interdecadal variations and examine them separately.

Previous studies of WNP TC climatology and teleconnections have examined data on a very broad horizontal scale (over the entire WNP). These studies, while elucidating many important potential relationships among WNP TC climatology, ENSO, WPSST, and NH 500 hPa geopotential heights, also demonstrated how WNP climatology would benefit from additional research given that important questions remain as to the exact nature of these relationships. This thesis will investigate the possible effects of limiting the horizontal extent and focusing correlation analyses on the highest TC frequency areas of the WNP, namely, whether the result obtained for the entire large WNP area is applicable to the smaller, more focused domain.

Chapter II will detail the data and methods that were used and Chapter III examines results. Chapter IV will have a summary of the results, implications, and concluding remarks.

# II. DATA AND METHODS

## A. OVERVIEW

To study the relationship between TC frequency in the WNP Pacific and summer teleconnections, a 51-year period of climatological data from 1951-2001 for TC frequency and 500 hPa geopotential heights were initially obtained for the summer months in the Northern Hemisphere (June – August). The data were compiled for two domains in the WNP where there were climatological maxima in TC frequency. The first domain was designated the "P" region for its location near the Philippines and encompassed an area between 10 to 20°N and 110 to 140°E. Two base points were also defined in this domain and were located at 20° N 115° E and at 20° N 130° E. The second domain was designated the "T" region and was located north of the P region near Taiwan. This domain encompassed an area between 21.25 to 30°N and 110 to 140°E. Figure 1 illustrates the size dimensions and locations for each domain.

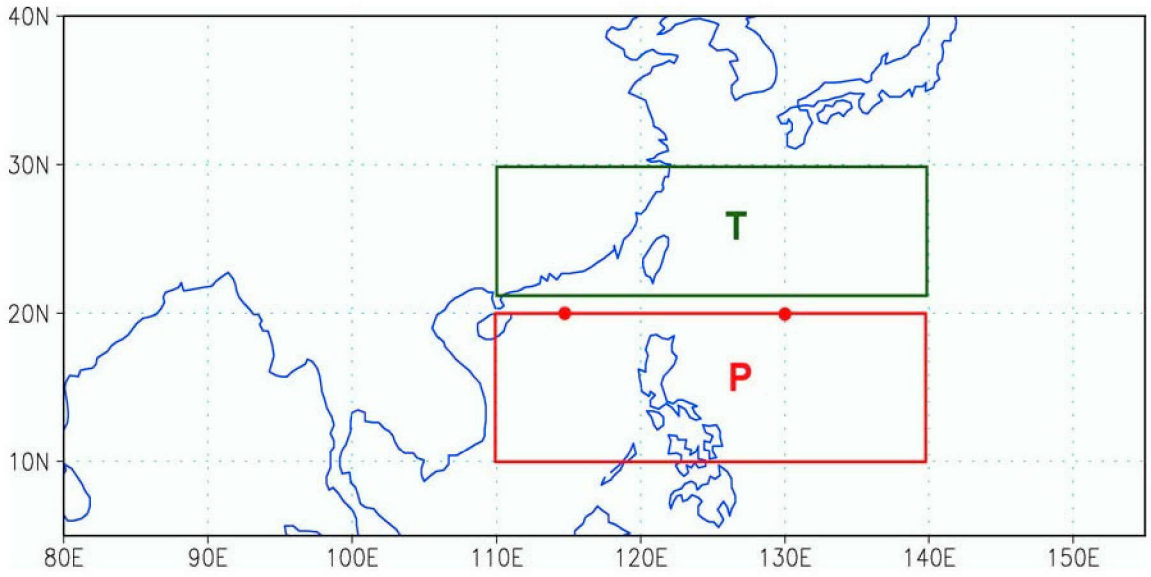



Figure 1. Locations and size dimensions for the P and T domains. P domain dimensions are 10 - 20° N, 110 - 140° E. Bold circles show base points, which are located at 20° N 115° E and 20° N 130° E. T domain dimensions are 21.25 - 30°N, 110 - 140°E.

## B. TC FREQUENCY DATASETS

The size and locations of the P and T domains and the base points for 500 hPa geopotential height were selected for their proximity to the maximum frequency of TC's as seen in Figure 2. The location of the geopotential height base points is chosen to be at 20°N, on the northern boundary of the P region. A choice of a lower latitude may cause problems due to small geopotential height fluctuations near the equator. This latitude also allows observations of energy dispersion into the westerlies. At lower latitudes, the presence of tropical easterly flow at 500 hPa prevents Rossby wave propagation and traps energy in the tropics.

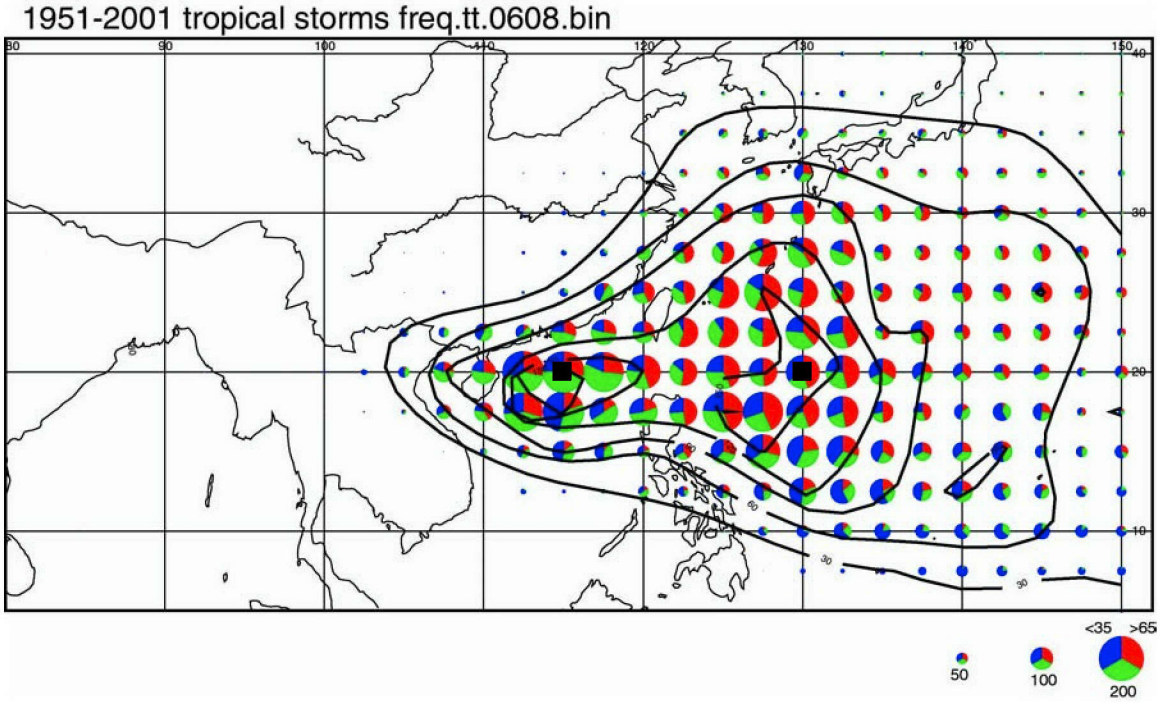



Figure 2. Seasonal TC frequency for the western Pacific from 1951-2001 (Jun – Aug). Size of individual frequency circles indicates number of tropical cyclones for a particular grid. Color indicates tropical cyclone intensity (i.e., blue for storms < 35 kts, green for storms ≥ 35 kts and ≤ 65 kts, and red for storms > 65 kts. Bold black boxes indicate locations of base points.

To calculate TC frequency, the P and T domains were sub-divided into 2.5° x 2.5° grids. Since the Joint Typhoon Warning Center (JTWC) assigns latitude and longitude (lat/lon) coordinates for each TC every 6 hours during a "watch window", each TC in the domain was counted against the appropriate grid every 6 hours that a storm was located in the domain. Thus, a slow-moving TC, for example, may be counted several times for one or more grids if the storm remained in the domain over several 6-hour watch windows. TC frequency at the base points was calculated in the same manner as each domain grid. Because the base points (as well as all other grids around the periphery of the domains) are located on the perimeter, the P and T domains consisted of an area slightly larger than that shown in Figure 1. Each domain was extended by 1.25° to give grids along the domain edge the same 2.5° x 2.5° area in which to calculate TC frequency. There was no overlap between the northern boundary of the P domain and the southern boundary of the T domain.

After determining TC frequency within the domains, the 51-year period of data was divided in half to designate "active" and "inactive" (also referred to as "less active") years. The domains were designated active by using the top 25 years with the highest recorded TC activity. Conversely, the domains were designated inactive using the bottom 25 years of the lowest TC activity (the $26^{th}$ record was not included in either category. TC indices were then created to (1) distinguish between active and less active periods of TC frequency; and (2) account for TC intensity. As seen in Figure 2, three categories of intensity were compiled: (1) TC's with winds > 65 kts, representing the category of typhoons according to the JTWC definition; (2) TC's with winds $\leq$ 65 kts and $\geq$ 35 kts, representing the category of tropical storms; and (3), TC's with winds < 35 kts representing the category of tropical depressions. TC1 was defined for the strongest storms (Category 1 above). Similarly, TC2 was the sum of Category 1 plus Category 2 (typhoons and tropical storms) storms. Finally, the TC3 index was defined for all TC strengths in total. These three TC indices were used for TC data in the P domain. However, only the all-category (TC3) index was used for the T domain.

## C. GEOPOTENTIAL HEIGHT AND MEAN WIND DATASETS

Geopotential height datasets were obtained from the joint Reanalysis Project archives of the National Center for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) for the period from 1951- 2001 (NCEP/NCAR 2005). The 500 hPa geopotential height data were used to construct one-point correlation analyses. These analyses were used to investigate potential geopotential height anomalies and teleconnections between the base points in the P region and all other points during the NH summer months. Mean wind datasets were also obtained from NCEP/NCAR to investigate the possible relationship to TC activity in the western Pacific.

## D. OTHER DATASETS

Additional datasets for SST's in the western Pacific (WPSST) were obtained from the National Climatic Data Center as part of their Extended Reconstructed Sea Surface Temperature (ERSST) archives (NCDC 2005). WPSST data covers an area between 5° - 30°N and 120° - 180°E. The Nino3.4 datasets were obtained from the Climate Diagnostics Center (CDC 2004). Nino3.4 data covers SST's in the east central tropical Pacific from 5° N to 5° S and from 120° W to 170° W. These data were obtained to investigate the possibility of significant correlations with geopotential heights in the P region and North America and this study's TC indices. Table 1 summarizes all of the parameters used in this study and the correlations calculated. The parameters will be defined in the subsequent sections when they are first introduced.

| | | | | | | |
|---|---|---|---|---|---|---|
| 1. | TC Index | P115 | | 6. | P115 | Nino3.4 |
| 2. | TC Index | NA1 | | 7. | P115 | WPSST |
| 3. | P115 | NA1 | | 8. | NA1 | Nino3.4 |
| 4. | TC Index | WPSST | | 9. | NA1 | WPSST |
| 5. | TC Index | Nino3.4 | | | | |

Table 1. Summary of correlation coefficients calculated among selected parameters

## E. REMOVING INTERDECADAL VARIATIONS IN THE TIME SERIES

The time series of all datasets were decomposed into interdecadal and interannual components. As was stated previously, this was done to exclude the possible influence of a significant interdecadal shift in the climate over the WP in the 1970s. The interdecadal variation of each parameter is estimated by performing a fourth-order polynomial fit on each of the time series. The interannual variation of each parameter is then determined by subtracting the interdecadal variation from the original time series.

## F. SIGNIFICANCE OF CORRELATION COEFFICIENTS

Correlations were carried out for time series of 51 years and 25 years. The statistical significance of the relationships is given by that of a t test and evaluated at 95 and 99% confidence levels. The correlation coefficients at these levels are dependent on the degree of freedom, which is determined by the sample size. A correlation coefficient is considered significant if it meets or exceeds the 95% confidence level, which is 0.275 for the 51-year series and 0.395 for the 25-year series, respectively. Significant correlation coefficients for the 99% confidence level are 0.355 for the 51-year series and 0.499 for the 25-year series, respectively.

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# III. RESULTS

## A. BASE POINT AND SEASON SELECTIONS

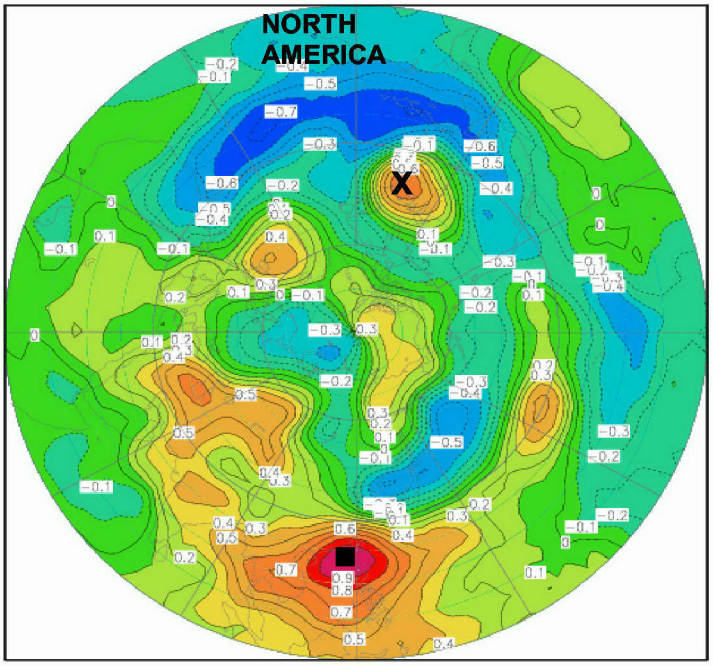
At the outset of the research, a hypothesis was made that when considering TC frequency in the WNP, increased TC activity would contribute to a greater signal on teleconnections than less active TC activity. This hypothesis was based on the premise that with more TC's present, one may observe more pronounced patterns or anomalies in the 500 hPa geopotential heights as a result of a stronger tropical forcing influence that, in turn, enters the westerlies and propagates eastward as Rossby waves. Thus, the signal of the potential teleconnection responses may be quite different between active and inactive periods.

Using the 51-yr period of TC frequency data for the P region, and compiled for the summer season (Jun – Aug), one-point correlation analyses were initially performed for base points at 20° N 115° E and 20° N 130° E to compare 500 hPa geopotential heights at these base points with all other points in the NH for total, active, and inactive levels of TC frequency. An in-phase relationship exists between the base point and all other points in the analysis when there is a significant positive correlation. An out-of-phase relationship exists with a significant negative correlation.

As stated previously, the frequency data were initially divided in half with the top 25 records designated active and bottom 25 records designated inactive (or less active). Using the 500 hPa one-point correlation coefficient analyses, the atmospheric responses for all 51 years, the 25 active years, and the 25 inactive years were compared for this 3-month period. Correlation coefficients were initially computed by individual month within the typhoon activity season each year, which lasts from June to November, by three-month seasons (June - August, September - November), and by year (June - November) for the 51-year period. However, after reviewing the data for the various time periods and consulting previous work in summer teleconnections, the calendar summer

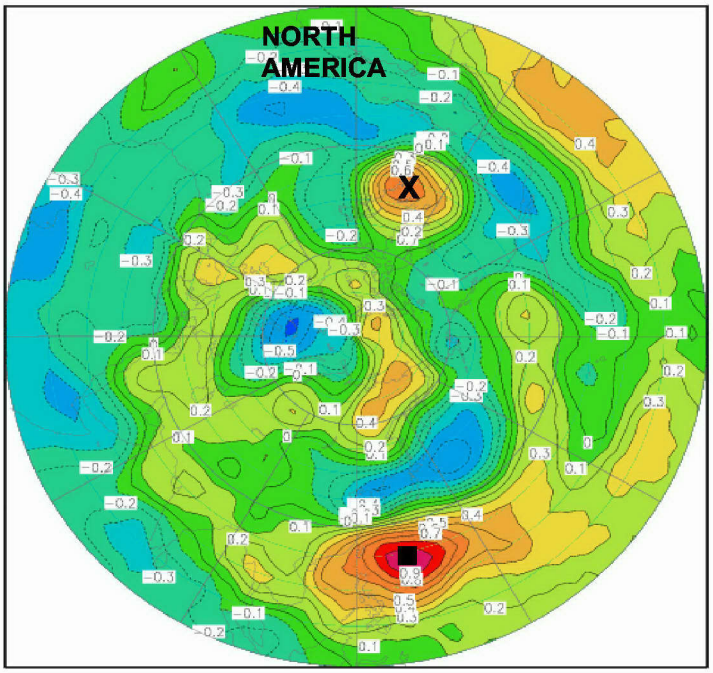
season of June – August was chosen for the investigation. Lim and Chang (1986) showed that a minimum of 2-3 weeks was required for a response from tropical forcing to enter the westerlies, propagate downstream, and to manifest itself as a statistically significant "signal" in the global circulation over North America. Monthly datasets showed considerable variations between adjacent months, which may be the result of the interruption of the signal of a TC if it lasts across two months. A period of longer than the June-August calendar summer season into autumn will include a larger change of the basic flow due to seasonal transitions. A study of the 3-month period of September – November may also be of interest, but time did not permit that investigation here.

Figures 3, 4, & 5 illustrate the results obtained from both base points for the active years, inactive years, and total period in the NH summer season. As stated previously, because the correlation coefficients over North America from both base points are not significantly different, the base point for 20° N 115° E (hereafter referred to as P115) was chosen to be used in all subsequent correlation calculations and comparative analyses.




Base point (■):
20° N 115° E

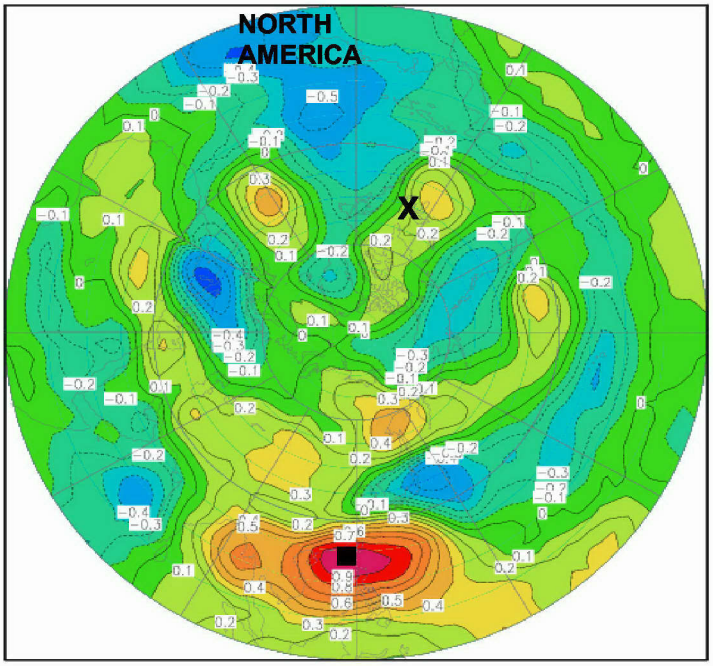
Active years




Base point (■):
20° N 130° E

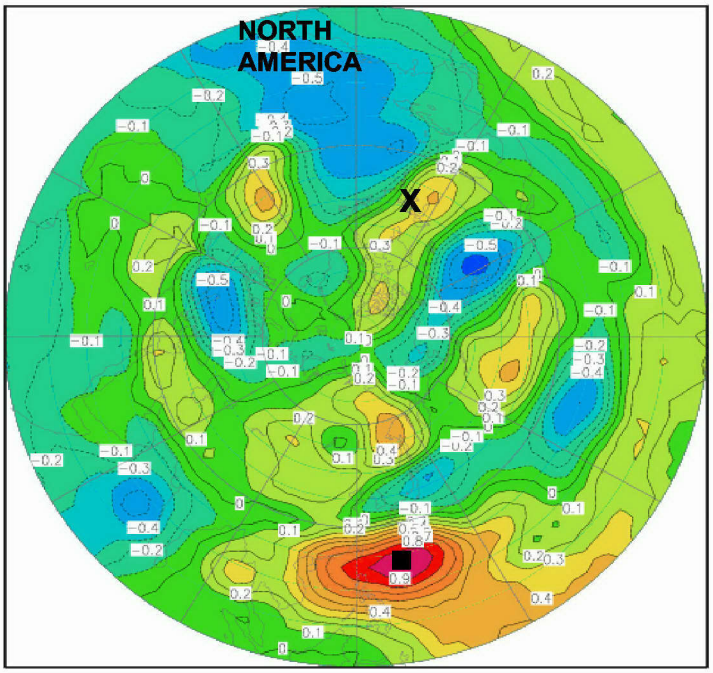
Active years

Figure 3. Correlation coefficients over North America from both base points in the P region during active TC years. (The symbol X indicates location of the parameter NA1, which is defined in Section III.B.)




Base point (■):
20° N 115° E

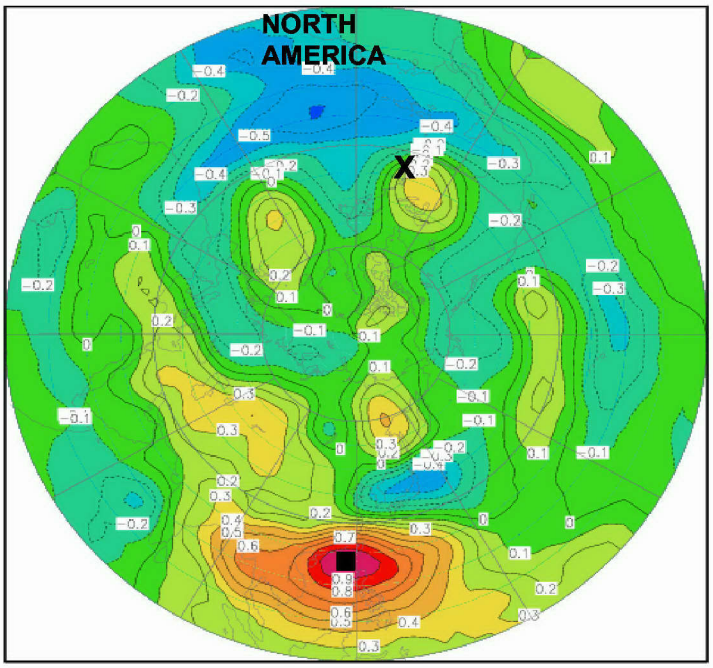
Inactive years




Base point (■):
20° N 130° E

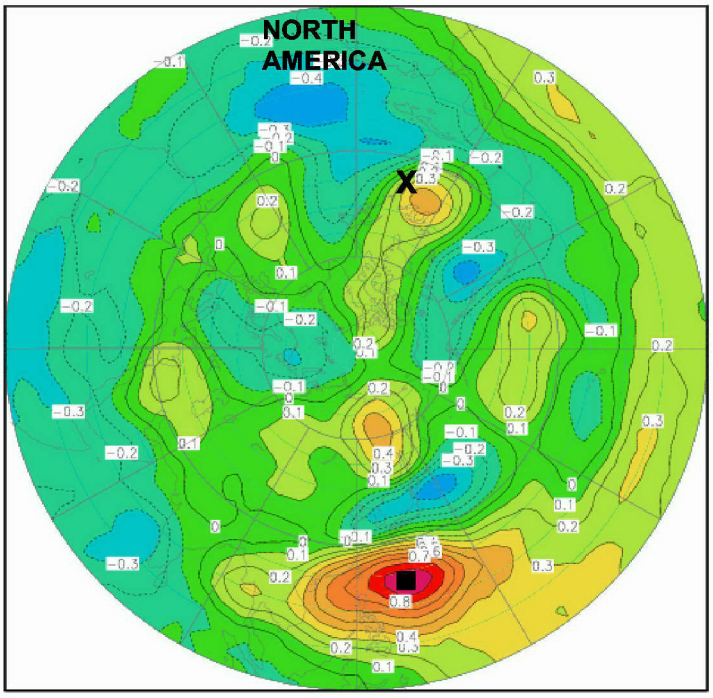
Inactive years

Figure 4. Correlation coefficients over North America from both base points in the P region during inactive TC years.




Base point (■):
20° N 115° E

(Total 51 years)




Base point (■):
20° N 130° E

(Total 51 years)

Figure 5. Correlation coefficients over North America from both base points in the P region for the total 51-year period.

## B. SINGLE-POINT CORRELATIONS FOR P115 TC INDICES AND NH GEOPOTENTIAL HEIGHTS

The results of the single-point correlation coefficients between P115 and NH geopotential heights for the active years, inactive years, and total period are shown in the top panels of Figures 3, 4 & 5, respectively. A teleconnection pattern between the P115 and North America is found in all three figures, with the pattern resembling a mixture of Lau and Weng's (2000) two modes, the zonally-elongated (Mode 1) and the wavetrain (Mode 2). These results show that the active years had a significant positive correlation of 0.6 between the geopotential heights at P115 and an area over North America centered near 37° N and 80° W. (Marked by the symbol "X" in Figures 3-5). The high-correlation North American domain roughly encompasses an area between 30 to 45° N and 70 to 90° W. The averaged 500 hPa geopotential height over this domain will be designated NA1. There was also a negative correlation of -0.5 over southern North America as well. For the inactive years, the highest correlation between P115 and the NA1 area is less than 0.4. For the total 51 years, the highest correlation is less than 0.5. Thus, an active frequency of TC's in the WNP seems to indicate a stronger positive correlation between 500 hPa geopotential heights at P115 and NA1 than when the TC frequency is less active.

## C. DIFFERENCE OF 500 HPA MEAN WINDS BETWEEN ACTIVE AND INACTIVE YEARS

Figure 6 is a composite 500 hPa mean wind for the inactive and active years, respectively. From this figure, it can be seen that the mean winds over the jet stream region are mostly stronger during inactive periods for nearly all longitudes as denoted by the darker shading and longer wind vectors. In a recent study, Ding and Wang (2005) suggested that the zonally-elongated teleconnection pattern, or Mode 1, in the teleconnection modes identified by Lau and Weng (2000) is sensitive to the mean flow. They made this suggestion by observing that in July, when the jet stream is weaker, this mode becomes more prominent. The results presented thus far, namely that the mean jet stream during active TC years is weaker compared to inactive years, and that the

teleconnection pattern is stronger during the active years, may therefore appear to suggest that the teleconnection pattern found in this study might be affected by the zonally-elongated mode (Mode 1) of Lau and Weng (2000).

Since TC activity has been found to have a relationship with El Nino/ Southern Oscillation (ENSO) (e.g., Wang and Chan 2002, Chan 2004), it is conceivable that the stronger teleconnection identified in the active TC years might be the result of ENSO influence rather than the TC activity. To clarify this question, we will examine the possible relationships between tropical Pacific SST and the TC and 500 hPa geopotential height indices used in this study. For tropical Pacific SST we will use both Nino3.4 SST to represent ENSO, and also SST's in the WNP (WPSST). By analyzing these relationships we hope to determine whether the stronger teleconnection during the active TC years is due to the influence of SST's. In the following sections we will present the correlations between the SST indices and the TC, P115 and NA1 indices.

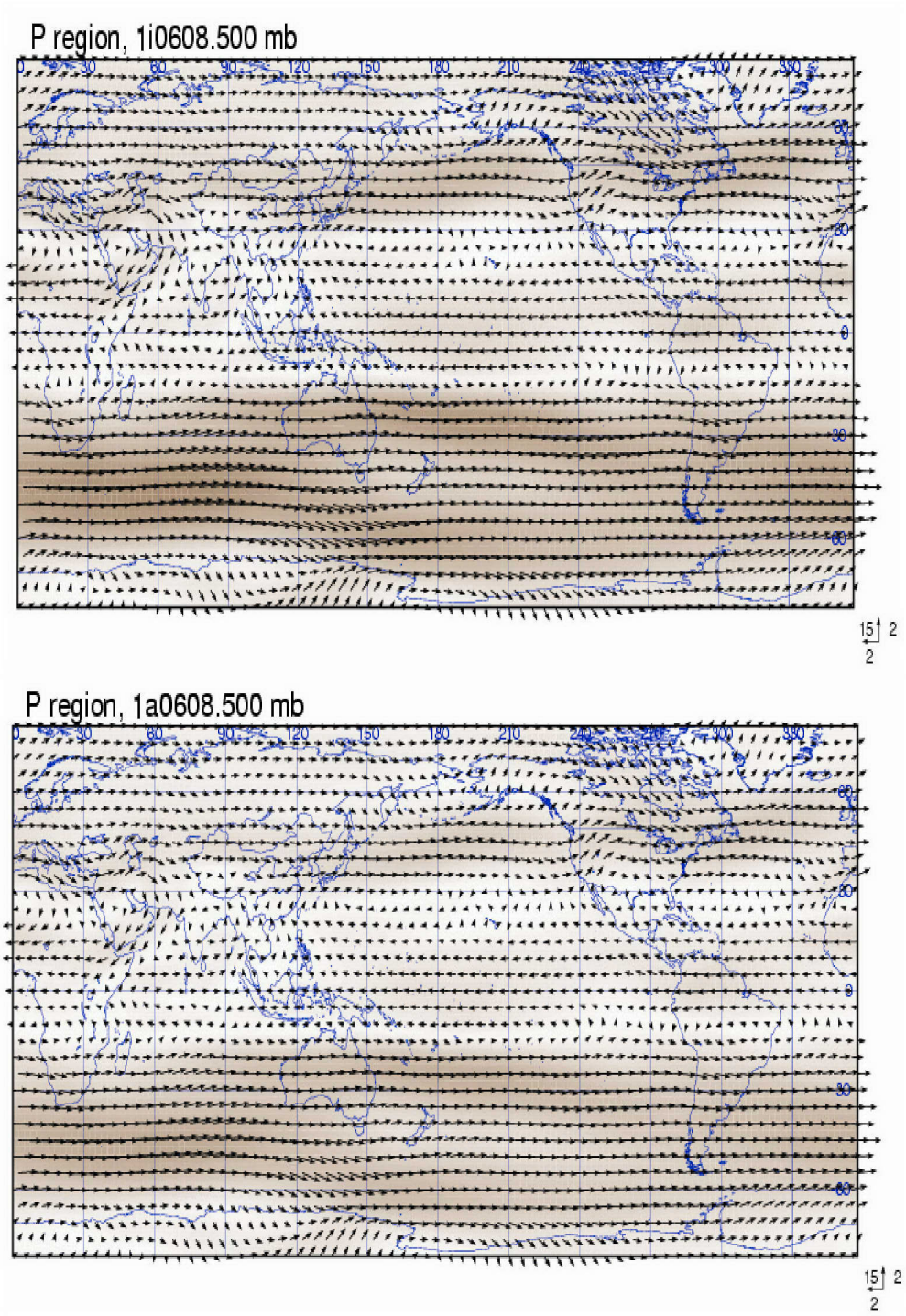



Figure 6. Analysis of mean winds during inactive (top graphic) and active TC years. Dark shading and longer wind vector lengths denote faster wind speeds.

## D. CORRELATIONS WITH SST INDICES FOR TOTAL (51-YEAR) PERIOD

| Table 2. | P Region 51-year correlation coefficients. Coefficients satisfying the 95% confidence level are bold-faced. |
|---|---|
| TC3-NO34 | **0.462** |
| TC3-WPSST | -0.045 |
| TC3-NA1 | 0.087 |
| TC3-P115 | 0.177 |
| NA1-NO34 | -0.130 |
| NA1-WPSST | **0.358** |
| NA1-P115 | **0.468** |
| P115-NO34 | 0.127 |
| P115-WPSST | 0.257 |

The possible influences of SST's are first examined for the total 51-year period. Table 2 outlines the single-point correlation coefficients that were calculated for the five parameters used in this study for the total 51-year period. These parameters are: (1) TC index; (2) P115; (3) NA1; (4) WPSST; and (5) Nino3.4 SST (NO34). As stated previously, the TC index can be broken down into TC1, 2, and 3 to account for TC intensities (i.e., TC1 are typhoons only, TC2 are typhoons and tropical storms, and TC3 are all-intensity categories of TC's), and P115 and NA1 refer to 500 hPa geopotential heights over the base point and averaged over the North American domain, respectively. For 51 years data, the 95% and 99% confidence levels are 0.275 and 0.355, respectively.

Table 2 shows a statistically significant relationship between P115 and the area-averaged NA1 index of 0.468. It shows that NO34 SST is significantly correlated with the total TC index TC3 with a coefficient of 0.462, which shows the influence of ENSO on TC activities. However, the NO34 SST is not significantly correlated with either the NA1 or the P115 indices. The WPSST has a positive correlation with NA1, but its correlations with TC3 and P115 are insignificant. Based on this result, it appears that the significant correlation in the

NA1-P115 teleconnection is not the result of direct correlation with the SST indices.

To ensure that the correlations shown in Table 2 are not the result of climatological trends that are due to long-term climate changes, the interdecadal trends were removed. This was done by calculating the 4$^{th}$ order polynomial fit, and subtracting it from the original time series. The resultant time series are considered to represent only interannual variations (IAV). Figure 7 shows the original times series and the interdecadal trend using the 4$^{th}$ order fit for the TC index. Table 3 shows the correlation coefficient results after interdecadal and IAV data were calculated. Results for the NA1-P115 correlation

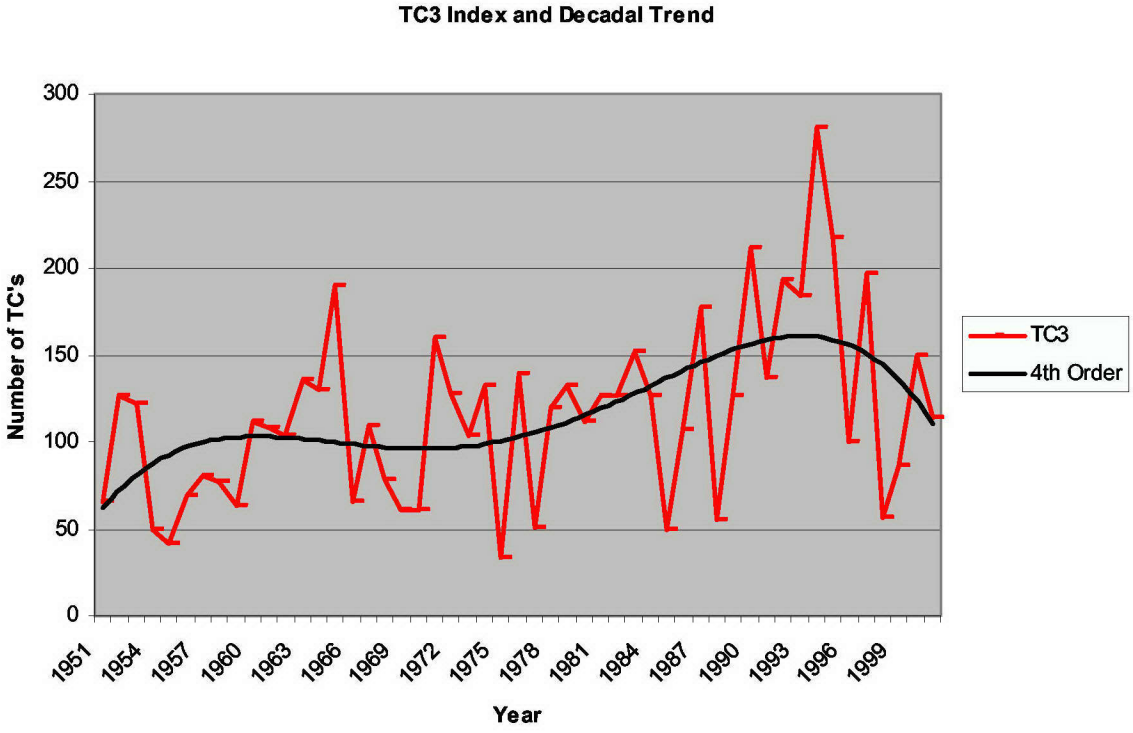



Figure 7. Time series showing TC Index (TC3) calculated in the P region for the 51-year period. Black line indicates decadal trend of index.

| Table 3. | P Region 51-yr correlation coefficients, including decadal and IAV data. Coefficients satisfying the 95% confidence level are bold-faced. | | |
|---|---|---|---|
| | **Original** | **Decadal** | **IAV** |
| TC3-NO34 | **0.462** | 0.691 | **0.474** |
| TC3-WPSST | -0.045 | 0.390 | -0.270 |
| TC3-NA1 | 0.087 | 0.456 | -0.014 |
| TC3-P115 | 0.177 | 0.840 | -0.265 |
| NA1-NO34 | -0.130 | 0.058 | -0.151 |
| NA1-WPSST | **0.358** | 0.249 | **0.425** |
| NA1-P115 | **0.468** | 0.672 | **0.389** |
| P115-NO34 | 0.127 | 0.383 | 0.145 |
| P115-WPSST | 0.257 | 0.145 | 0.271 |

show a high coefficient value of 0.672 at the interdecadal time scale. However after the decadal variations are subtracted, there is still a correlation coefficient of 0.389 between NA1 and P115, which is significant at the 99% confidence level. This result indicates that the NA1-P115 correlation is not simply the result of a coherent long-term trend, but rather that there is indeed a year-to-year relationship between the 500 hPa geopotential heights at these two points during the Northern Hemisphere summer. Table 3 also shows that the NO34-TC3 and the NA1-WPSST correlations remain significant after the decadal trends are removed.

## E. CORRELATIONS WITH SST INDICES FOR 25 ACTIVE YEARS AND 25 INACTIVE YEARS

In this section, the IAV correlations among the relevant parameters are computed for the 25 active years and the 25 inactive years, respectively, by again removing the interdecadal variations as represented by a $4^{th}$ order polynomial fit. These results are displayed in Table 4. The first result is that the significant correlation between TC3 and ENSO is valid only during the inactive years after the removal of the decadal trend.

In the "Original" column of Table 4, the NA1-P115 correlation coefficients of 0.500 and 0.449, respectively, are both significant. Upon closer inspection, the NA1-P115 correlation is found to be significant only for active years. When

Table 4. Correlation coefficients for active and inactive 25 years using original, decadal, and IAV data. Coefficients satisfying the 95% confidence level are bold-faced.

| | Original | | Decadal | | IAV | |
|---|---|---|---|---|---|---|
| | **Active 25** | **Inactive 25** | **Active 25** | **Inactive 25** | **Active 25** | **Inactive 25** |
| TC3-NO34 | 0.303 | 0.379 | 0.853 | 0.572 | 0.185 | **0.556** |
| TC3-WPSST | 0.267 | 0.133 | 0.455 | 0.522 | -0.189 | -0.005 |
| TC3-NA1 | 0.051 | 0.080 | 0.498 | 0.337 | -0.006 | 0.101 |
| TC3-P115 | 0.270 | -0.130 | 0.872 | 0.788 | -0.092 | -0.153 |
| NA1-NO34 | -0.124 | -0.258 | 0.303 | -0.174 | -0.188 | -0.088 |
| NA1-WPSST | **0.431** | 0.317 | 0.263 | 0.207 | **0.586** | 0.209 |
| NA1-P115 | **0.500** | **0.449** | 0.661 | 0.643 | **0.487** | 0.282 |
| P115-NO34 | 0.343 | -0.209 | 0.626 | 0.079 | **0.421** | 0.070 |
| P115-WPSST | 0.162 | **0.484** | 0.212 | 0.214 | 0.011 | **0.406** |

decadal trends with correlations higher than 0.6 are removed, the active years still have a significant 0.487 correlation. (For 25 years of data, the 95% and 99% confidence levels are 0.395 and 0.499, respectively). In contrast, the original correlation for inactive years appears to be mostly the result of decadal trends as it becomes reduced to a statistically insignificant 0.282 when decadal trends are eliminated. Thus, removing long-term trends has revealed that the NA1-P115 is significantly correlated only during active TC years. The inactive-year teleconnection pattern shown in Figure 4 therefore needs be considered insignificant.

Table 4 also examines whether the SST anomalies both in the eastern tropical Pacific through ENSO and in the WP may give rise to the apparent NA1-P115 correlation. The last row of Table 4 shows that P115 is significantly correlated with WPSST during inactive years. The P115-WPSST relationship shows a 0.484 overall and 0.406 IAV correlation, which suggests a significant relationship independent of interdecadal climate changes similar to the NA1-

P115 relationship during active TC years. The P115-NO34 IAV correlation of 0.421 is significant during active years, but this relationship may be the result of a strong interdecadal trend influence as seen in the significant interdecadal correlation of 0.626. Therefore, P115 appears to be more strongly correlated with WPSST, but only during inactive TC years.

The NA1 relationships with WPSST and NO34 reveal different results. Table 4 indicates that NA1-WPSST is significantly correlated only during active TC years and that NA1-NO34 is not significantly correlated during either active or inactive years. Specifically, the NA1-WPSST shows a 0.431 correlation during active years with no significant decadal correlation present. Unlike the P115-NO34 relationship, which shows a significant borderline correlation of 0.343, the NA1-NO34 is statistically insignificant. Table 5 is a subset of Table 4 and summarizes the key points and relationships discussed thus far.

Table 5. Summary of key P115/NA1 correlations with WPSST and NO34. Coefficients satisfying the 95% confidence level are bold-faced.

| | Original | | Decadal | | IAV | |
|---|---|---|---|---|---|---|
| | **Active 25** | **Inactive 25** | **Active 25** | **Inactive 25** | **Active 25** | **Inactive 25** |
| **NA1-P115** | **0.500** | **0.449** | 0.661 | 0.643 | **0.487** | 0.282 |
| P115-WPSST | 0.162 | **0.484** | 0.212 | 0.214 | 0.011 | **0.406** |
| NA1-WPSST | **0.431** | 0.317 | 0.263 | 0.207 | **0.586** | 0.209 |
| P115-NO34 | 0.343 | -0.209 | 0.626 | 0.079 | **0.421** | 0.070 |
| NA1-NO34 | -0.124 | -0.258 | 0.303 | -0.174 | -0.188 | -0.088 |

From Table 5, some general conclusions about the nature of the NA1-P115 relationship can be derived. P115 and NA1 independently do not share a common correlation with ENSO or WPSST. The latter parameters impact P115 and NA1 differently. WPSST is related to P115 only during inactive TC years, but is related to NA1 only during active years. In addition, ENSO shows a significant correlation with P115 during active years, but it shows a very low correlation with NA1 for all levels of TC activity. Thus, based on these

correlations, the NA1-P115 correlation is apparently not a by-product of the influence by either ENSO or WPSST.

## F. TELECONNECTION PATTERNS USING THE T REGION TC ACTIVITY

In this section, we evaluate whether the result of a stronger teleconnection with more active TC's in the P region also applies if the TC activity is measured in the T region. This will be done by comparing the teleconnection patterns related to P115 based on the TC activity in the P and T regions. Figure 8 shows the patterns during active (upper panel) and inactive (lower panel) years in the P region, and Figure 9 shows those in the T region. We plot these figures in Mercator projection to give another perspective that may help the visual association of the teleconnection patterns with the two principal modes identified by Lau and Weng (2000).

Figure 8 shows that the teleconnection between P115 and North American 500 hPa geopotential heights is stronger during active years than inactive years. The correlation coefficients near the center of NA1 are near 0.6 for active years and 0.3 for inactive years. In this figure, the teleconnection between P115 and NA1 resembles the zonally-elongated mode (Mode 1) of Lau and Weng (2000), even though some aspects of a wavetrain-type pattern are also present. Another teleconnection linking the western North Pacific and North Atlantic may be seen by following a more polar route. This route is closer to the great circle, which is characteristic of wavetrain-type teleconnections (Mode 2 of Lau and Weng 2000). It therefore seems again that the NA1-P115 teleconnection may be mainly Mode 1 of Lau and Weng (2000).

Figure 9 shows that the teleconnection patterns based on the typhoon activity in the T region are shifted only slightly from those based on the activity in the P region. Overall, the North American domain, seen in the upper right quadrant of each map, is most significantly correlated with the WNP during the active TC years. The positive correlation over eastern North America for T region active years is smaller and weaker (center around 0.5) than that based on

the P region active years. For inactive years, the correlation is the same (center around 0.3) as that based on P region activity. Therefore, it appears that the difference between active and inactive years based on the T region activity is slightly reduced from that based on the P region activity. This may be due to a smaller number of TC's in the T region than the P region (Figure 2), which makes the separation of the active and inactive years less distinctive.

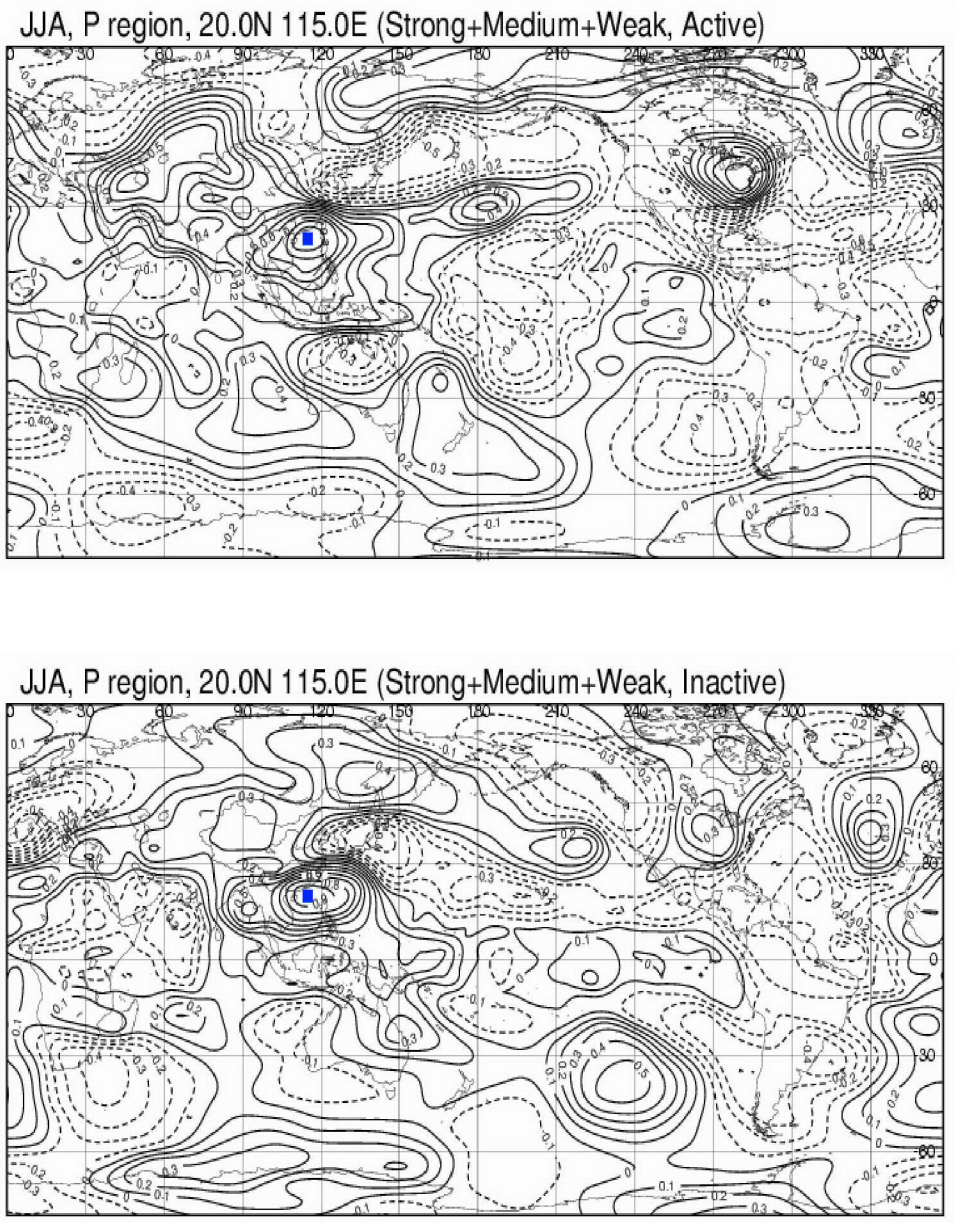



Figure 8. Global teleconnection patterns resulting from using the P115 base point, active (top panel) and inactive years, with TC3 index (typhoons, tropical storms, and tropical depressions) in the P region for June - August (JJA) . Bold blue box marks the location of P115. North America can be seen in the upper right quadrant of each map.

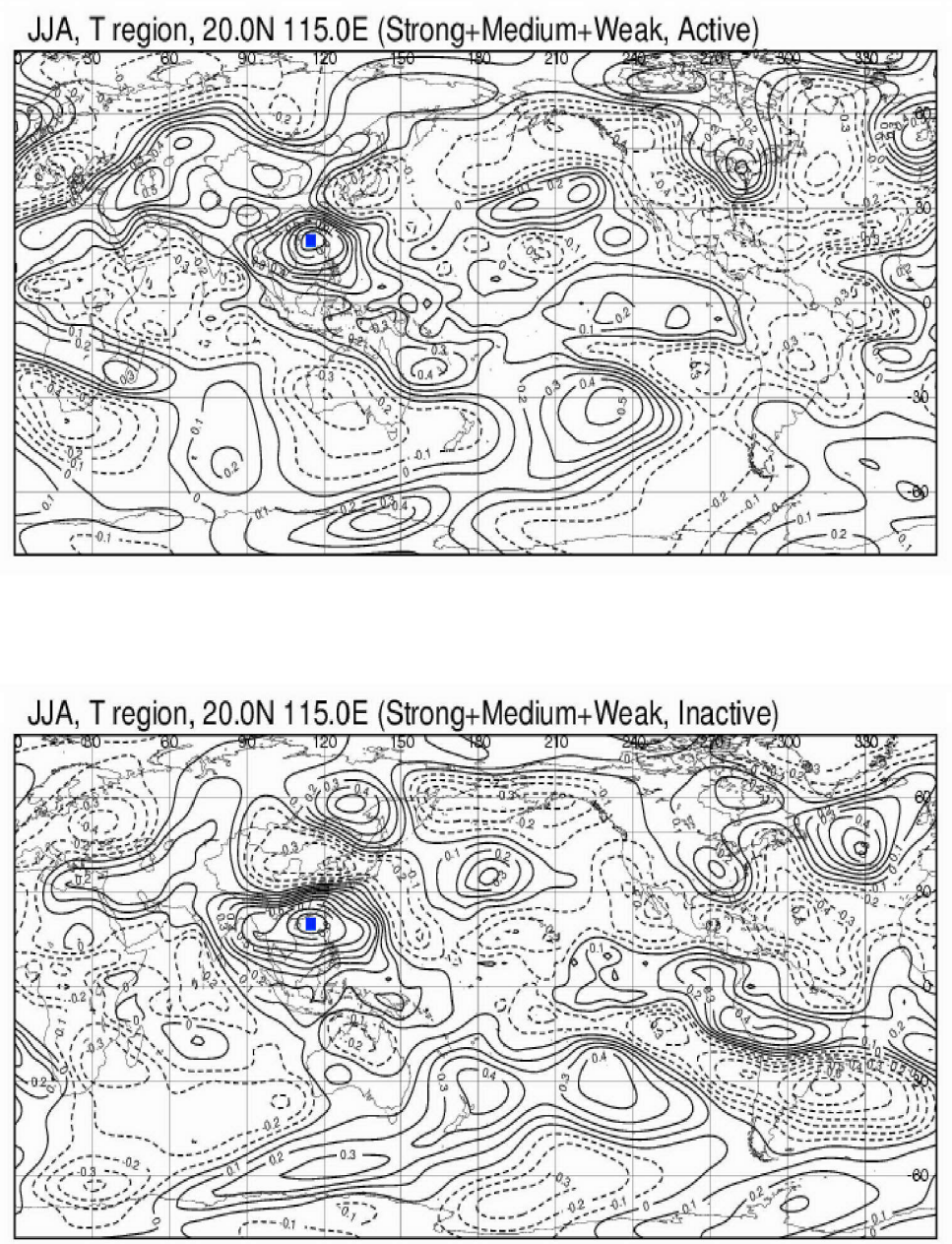



Figure 9. Global teleconnection patterns resulting from using the P115 base point, active (top panel) and inactive years, with TC3 index (typhoons, tropical storms, and tropical depressions) in the T region for June - August (JJA) . Bold blue box marks the location of P115. North America can be seen in the upper right quadrant of each map.

The previous results, in which all TC intensities were used (TC3), were then verified with teleconnection patterns in which only typhoons are included (TC1). Figures 10 and 11 show that this correlation is similar to that for the TC3 index. Namely, active TC years show a significant correlation between P115 and North America, but inactive years have an insignificant correlation. The difference between active and inactive correlations is again larger for the P region compared to the T region, with the T region showing and even smaller difference compared to the TC3 results (0.5 active/0.4 inactive).

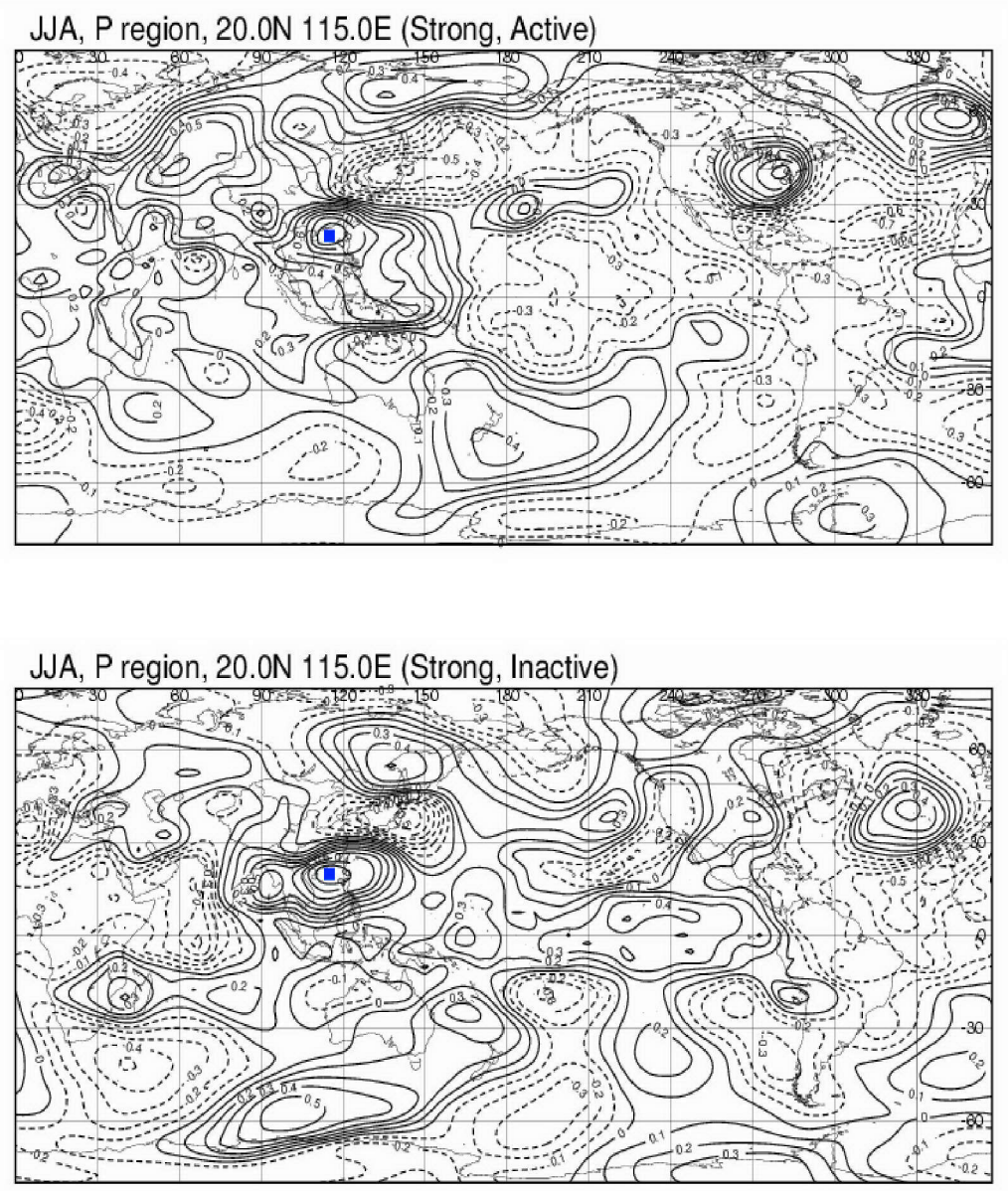



Figure 10. Global teleconnection patterns resulting from using the P115 base point, active (top panel) and inactive years, with TC1 index (typhoons only) in the P region for June - August (JJA) . Bold blue box marks the location of P115. North America can be seen in the upper right quadrant of each map.

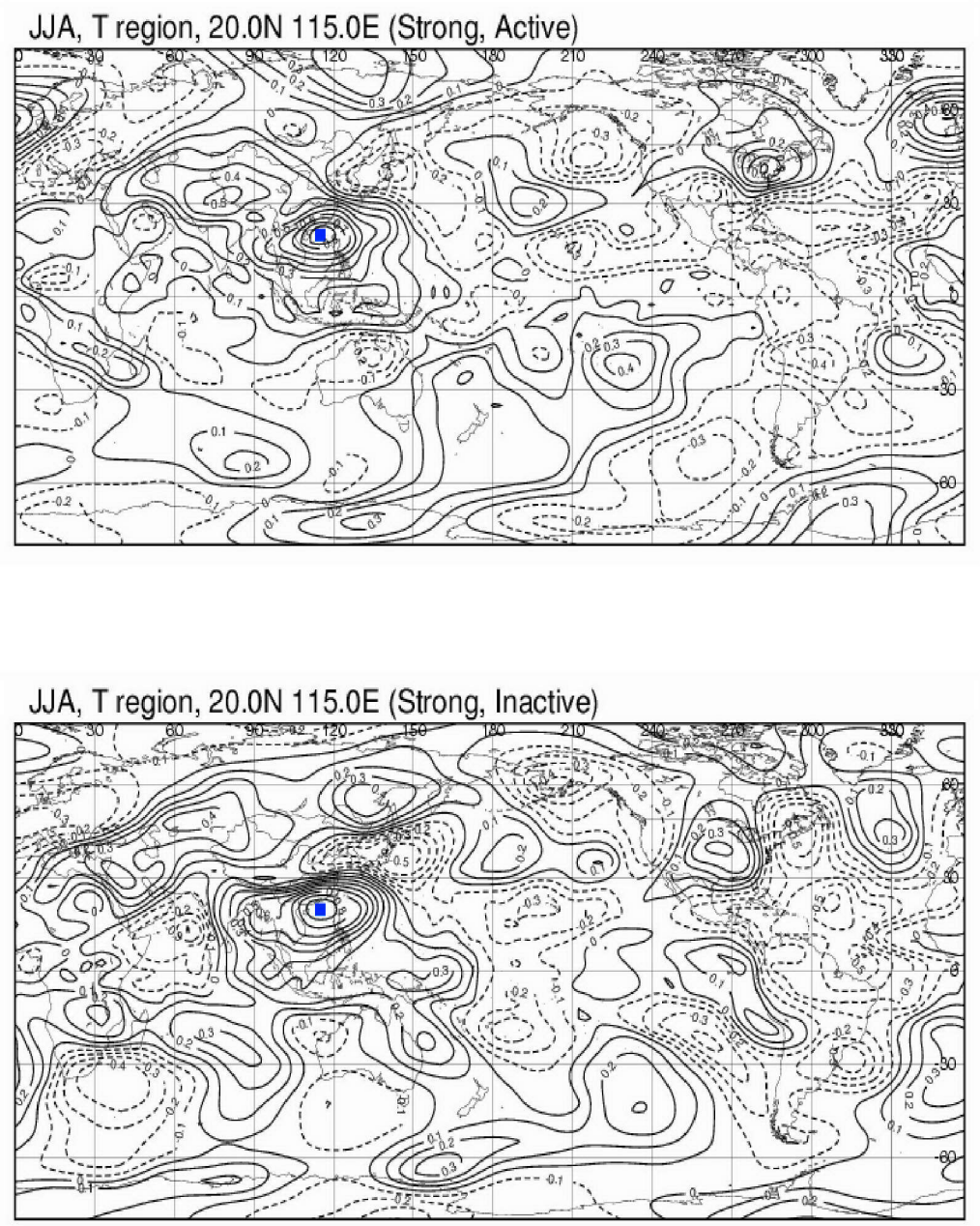



Figure 11. Global teleconnection patterns resulting from using the P115 base point, active (top panel) and inactive years, with TC1 index (typhoons only) in the T region for June - August (JJA) . Bold blue box marks the location of P115. North America can be seen in the upper right quadrant of each map.

## G. EFFECTS OF TC INTENSITIES ON CORRELATIONS

In this section, we will address the question of whether different TC intensities may change the correlations between different parameters. Previously, Tables 2-4 showed correlations based on the TC3 index that includes all three intensities: typhoons, tropical storms, and tropical depressions. Here we will compare the correlations of the three different TC indices with the SST indices and with the 500 hPa geopotential height indices. The three TC indices defined earlier are TC1 (typhoons only), TC2 (typhoons and tropical storms), and TC3. They were correlated with P115, NA1, WPSST, and NO34. For these correlations, interdecadal variations were not removed, and the total period of 51 years was used. These comparisons were performed for the P, T, and P + T regions, where P + T is the combined area of both the P and T regions.

Table 6 shows the correlations for the P region. It can be seen that all three levels of TC intensities are significantly correlated with ENSO. In particular, the TC2 (typhoons + tropical storms) index yields the highest correlation coefficient of 0.626, which is higher than when only typhoons (TC1) are included. The correlation is actually the lowest when all TC intensities are included (TC3). Table 6 also shows that all three TC indices have no significant correlation with the other parameters, WPSST, NA1, or P115. The lack of significant correlation between the TC indices and WPSST is consistent with Chan and Liu (2004) who also noted that typhoon activity does not significantly correlate with local SST.

Table 7 contains the correlation coefficients for the T region, which is located to the north of the P region. Based on these results, it appears that the influence from ENSO on TC's does not extend northward as it did in the P region. However, there are somewhat weak but nevertheless significant negative correlations between most TC indices and P115 and NA1. These correlations probably reflect an effect of TC's on the 500 hPa geopotential height at the P115 point. Because P115 and NA1 are positively correlated, there is a likelihood of a TC-NA1 negative correlation. The reason that these TC-500 hPa height correlations are absent when the P region TC indices are used is less clear.

| Table 6. | P region correlation coefficients (51 years). Coefficients satisfying the 95% confidence level are bold-faced. |
|---|---|
| TC1-NO34 | **0.582** |
| TC2-NO34 | **0.626** |
| TC3-NO34 | **0.462** |
| TC1-WPSST | -0.268 |
| TC2-WPSST | -0.222 |
| TC3-WPSST | -0.045 |
| TC1-P115 | -0.207 |
| TC2-P115 | -0.026 |
| TC3-P115 | 0.177 |
| TC1-NA1 | -0.197 |
| TC2-NA1 | -0.035 |
| TC3-NA1 | 0.087 |
| NA1-NO34 | -0.130 |
| NA1-WPSST | **0.358** |
| NA1-P115 | **0.468** |
| P115-NO34 | 0.127 |
| P115-WPSST | 0.257 |

| Table 7. | T region correlation coefficients (51 years). Coefficients satisfying the 95% confidence level are bold-faced. |
|---|---|
| TC1-NO34 | 0.153 |
| TC2-NO34 | 0.047 |
| TC3-NO34 | -0.109 |
| TC1-WPSST | -0.215 |
| TC2-WPSST | -0.173 |
| TC3-WPSST | -0.130 |
| TC1-P115 | **-0.300** |
| TC2-P115 | **-0.373** |
| TC3-P115 | **-0.286** |
| TC1-NA1 | **-0.336** |
| TC2-NA1 | **-0.284** |
| TC3-NA1 | -0.253 |

| Table 8. | P + T region correlation coefficients (51 years). Coefficients satisfying the 95% confidence level are bold-faced. |
|---|---|
| TC1-NO34 | **0.487** |
| TC2-NO34 | **0.453** |
| TC3-NO34 | **0.297** |
| TC1-WPSST | **-0.314** |
| TC2-WPSST | -0.260 |
| TC3-WPSST | -0.100 |
| TC1-P115 | **-0.326** |
| TC2-P115 | -0.256 |
| TC3-P115 | -0.010 |
| TC1-NA1 | **-0.341** |
| TC2-NA1 | -0.204 |
| TC3-NA1 | -0.062 |

Finally, Table 8 shows results for the P and T regions combined (P + T). The significant correlations for the top two TC intensities and ENSO are the result of the correlation in the P region. The inclusion of the T region's tropical storms causes the TC3 correlation with ENSO to fall below significance. The P + T data also shows significant correlations between TC1 and WPSST, P115 and NA1. These correlations are -0.314, -0.326, and -0.341, respectively. The TC1-P115 and the TC1-NA1 negative correlations may be the result of the correlation signals contained in the T region results (Table 7). The out-of-phase relationship between TC1 and WPSST indicates that when the domain of the TC is combined so that the number of TC's approaches the total over the WNP, the cooling of the area-averaged SST by the summation of TC activity begins to become evident.

It appears then from the results presented here that a correlation does indeed exist between the WNP and North America, and its signal is indeed clearer during more active TC years that we initially hypothesized.

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# IV. SUMMARY AND CONCLUSION

The objective of this thesis was to test the hypothesis that summertime (June - August) teleconnection patterns observed between the WNP and North America may be stronger during more active TC years. This investigation was done by separating the 51-year (1951-2001) data into active and inactive years depending on the TC frequency in two domains in the WNP where the climatological average of TC frequency is highest. These two domains are the P region, which encompassed an area between 10 to 20°N and 110 to 140°E, and the T region, which encompassed the area between 21.25 to 30°N and 110 to 140°E. These domains are near the Philippines and Taiwan, respectively. We then performed single-point correlations of the 500 hPa geopotential heights between a base point at 20°N 115°E (referred to as P115), which represents the tropical heat source region, and a domain over North America (referred to as NA1). These correlations were done over the total 51-year period of data as well as for the 25 most active TC years and 25 least active TC years as computed for the two domains. For the P region, this apparent NA1-P115 correlation was found to be the strongest during the active TC years, in which a significant correlation of 0.6 was found. During the inactive years, the correlation falls to around 0.3, which is below the 0.395 threshold for the 95% confidence level. For the T domain, the difference between the active and inactive periods is reduced, with a correlation of around 0.5 for the former and 0.3 for the latter.

We then computed composite 500 hPa mean winds for the active and inactive TC years in order to find possible explanations for the stronger NA1-P115 correlation. These results showed the 500 hPa mean winds were weaker during the active TC years. The results of the mean jet stream being weaker during active years and a stronger signal of the teleconnection pattern during active years suggests that the pattern observed here is consistent with Lau and Weng's (2000) Mode 1 (zonally-elongated) teleconnection pattern. However, elements of their Mode 2 (wavetrain) pattern were also present in our results.

The NA1-P115 correlation was also verified against other climatological variables that have been known to influence global weather patterns to rule out the possibility that this relationship is the result of an external factor. Because a relationship between TC activity in the WNP and the El Nino/Southern Oscillation (ENSO) has been reported previously, we performed correlations among WNP TC frequency and intensity data, the P115 and NA1 500 hPa geopotential heights, western Pacific SST (WPSST), and Nino3.4 SST, which represents ENSO, in order to determine if the P115 – NA1 correlation might be the result of influences by these SST's. In these correlations, the possible influences of interdecdal variations were removed by subtracting a $4^{th}$ order polynomial fit to each of the time series. The results show that WPSST is significantly correlated with NA1 only during active years and with P115 only during inactive years. The correlation with ENSO was statistically insignificant with both NA1 and P115, but after interdecadal trends were removed from the data, ENSO showed a significant correlation with P115 during active TC years. However, the lack of common correlation between NA1, P115 and the other variables demonstrated that the NA1-P115 relationship is unlikely to be the result of a direct, linear influence of the SST's.

We also examined the results by separating the TC activity according to intensity. The indices TC1, TC2, and TC3 were defined to include typhoons, typhoons and tropical storms, and all-intensity TC's (typhoons, tropical storms and tropical depressions), respectively. These indices were applied to the P, T, and P + T regions, where P + T is the combined area of the P and T domains. The purpose of these indices was to investigate how the three categories of TC intensities from the three regions may correlate differently with ENSO, WPSST, and 500 hPa geopotential heights. ENSO was found to be significantly correlated with TC activity in the P region, but not the T region. Because of the influence of P region data, ENSO also had a significant correlation with TC activity in the P + T region. The ENSO-TC correlation is stronger for the more intense TC's (TC1 and TC2) and weaker for TC3. The other SST parameter, WPSST, had a significant negative correlation with TC activity when the P + T

region was considered, but not when the P and T regions were considered separately. This result is likely reflecting the greater number of storms over a wider area and the effect of cooling the area-averaged SST's in the larger domain.

We also computed the correlation coefficients between the TC indices and the geopotential heights at NA1 and P115 for the different regions. There were significant correlations between geopotential heights at P115 and NA1 and TC frequency in the T region, but not the P region. The correlations between TC activity in the T region and geopotential heights at P115 may reflect an effect from the TC's on the 500 hPa geopotential heights at the P115 point. Because P115 and NA1 are positively correlated, it is also likely that a negative correlation exists between TC-NA1. It is unclear, however, why these TC-500 hPa geopotential height correlations are not present when P region TC indices are used.

There are clearly interdecadal trends in the TC time series, such that our results may be subject to additional interpretations. The active years tended to be toward the latter half of the 51-year period (Figure 7). One possible explanation for this trend is that the introduction of satellite technology enhanced our ability to observe and track TC's over the open ocean. This may have had the effect of increasing the numbers of TC's in the WNP in the second half of the 51-year period and giving the impression that more TC's were occurring during this time. It is possible that earlier data do not reflect all of the TC activity that was taking place because of our more limited observing capability. More research is needed to explain these interdecadal variations in TC activity in the WNP beyond our observing capability, however. There may also be other physical mechanisms not addressed in this study that affect TC activity in the WNP and potentially North American climate.

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